Moist Processes in the GEOS-5 AGCM

Julio Bacmeister
julio.bacmeister@gsfc.nasa.gov

This note describes version 1 of the Moist Physics parameterizations (Moist-1) for the GEOS-5 system. Moist-1 is similar to the scheme used in the NSIPP-2 AGCM which was used in GMAO's initial contributions to Climate Process Team on Tropical clouds (Chris Bretherton, PI), and in the ITCZ study of Bacmeister et al. (2005). Major differences between NSIPP-2 moist physics and Moist-1/GEOS-5 are noted below. We expect further modifications to the moist physics to occur before GEOS-5 system delivery in April 2005. These will be described in revisions to this note as required.

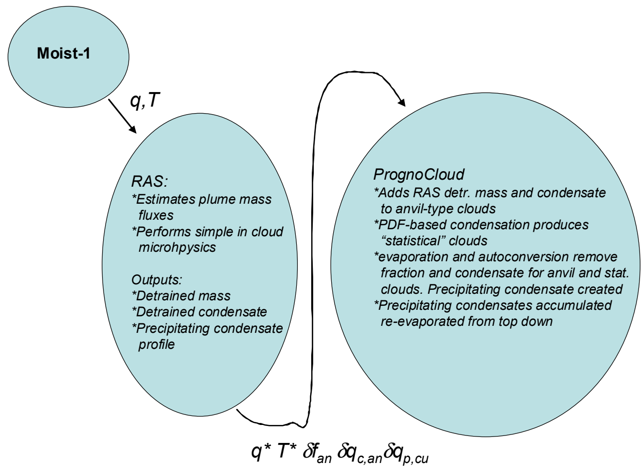
Moist-1 uses a single phase prognostic condensate and a prognostic cloud fraction. Two separate cloud "types" are recognized explicitly, with separate fraction and condensate variables kept for each type. The cloud types are distinguished by their source. One type, which will be denoted *"anvil" cloud*, originates in detraining convection. The second type, which we will refer to as *large-scale cloud*, originates in a PDF based condensation calculation. Once created, condensate and fraction from the anvil and large-scale cloud types experience the same loss processes: evaporation, autoconversion, sedimentation and accretion. Parameter settings may vary by type, but identical formulations are used. Clouds associated with updraft cores are not treated prognostically, but rainfall from convective cores is disposed of within Moist-1.

The basic sequence of events in Moist-1 is as follows. First, the convective parameterization, Relaxed Arakawa-Schubert, or RAS (Moorthi and Suarez, 1992) is called. RAS estimates convective mass fluxes for a sequence of idealized convective plumes. Each plume produces detraining fluxes of mass and cloud condensate, as well as profiles of precipitating condensate. Adjustments to the environmental profiles of u, v, T and q are also made sequentially by each plume.

Next, the large-scale cloud condensate scheme (PrognoCloud) is called. PrognoCloud first takes the detraining mass and condensate fluxes from RAS, if any exist, and adds them to the existing condensate and fraction of the anvil cloud type. Next, large-scale condensation is estimated using a simple assumed PDF of qtotal. This step produces a new fraction and condensate for the large-scale cloud type.

At this point all sources of condensate have been taken into account. Now four loss mechanisms are invoked: 1) Evaporation of condensate and fraction, 2) Autoconversion of liquid or mixed phase condensate, 3) Sedimentation of frozen condensate and 4) Accretion of condensate by falling precipitation. Each of these losses is applied to both anvil and large-scale cloud types. The formulation of these terms is detailed below.

In addition to producing and disposing of condensate, PrognoCloud handles the fallout of autoconverted (precipitating) condensate. Precipitating condensate is accumulated from the top down. In each model layer a typical drop size, fall speed, and residence time is estimated. These parameters are used to estimate re-evaporation of falling precipitation. These calculations are done separately for precipitation originating from each of the two cloud types, as well as for convective core precipitation. Note that a profile of autoconverted condensate within convective updrafts is an output of RAS.



A schematic diagram of Moist-1 is shown in Figure 1. The remainder of this note examines each process within Moist-1 in greater detail.

Convection

Moist-1 uses a modified version of the scheme described by Moorthi and Suarez (1992). As in Moorthi and Suarez a sequence of linearly entraining plumes is considered with mass flux profiles given by

$$\phi_k(z) = \phi_{0k}(1+\lambda_k z) \ .$$

The entrainment parameter λ_k is determined by the choice of cloud base and cloud detrainment level. Our implementation is flexible in this respect. The default is to take an average of the two lowest model layers as the cloud-base layer. In NSIPP-2 a random selection of 30 detrainment levels from a uniform distribution in σ was made. In GEOS-5 each model layer is tested, starting from the model level at 100 hPa and moving down to the level above cloud base. This choice does not appear to have a major impact on model behavior as long as roughly similar numbers of plumes are invoked.

Once cloud base, detrainment level, and λ_k have been chosen a series of calculations is made for the plume. A modified CAPE-based closure is used to determine the cloud base mass flux, ϕ_{0k}. In-plume budget equations for any quantity χ can be written once λ_k and ϕ_{0k} are known

$$\partial_z \phi_k \chi_k + \phi_{0k} \lambda_k \chi_E + D_k \chi_k = S_k$$

Here χ_E represents the environmental value brought into the plume by entrainment. D_k is the detraining mass flux, which is nonzero only at the detrainment level z_{Dk}. In the case of condensate q_{cc}, the term S_k represents a source from condensation and a sink due to autoconversion. Condensation within plumes is simply treated by removing any excess saturation with respect to the in-plume temperature. Autoconversion of convective condensate q_{cc} to precipitating condensate q_{pc} is treated following Sud and Walker

(1999), that is, an updraft velocity profile $w_k(z)$ is estimated for each plume and then used to derive time-scales $\Delta z/w_k$ for parcels rising through the plume. These time scales are then employed in simple temperature-dependent, Sundquist-type expressions for autoconversion

$$\delta q_{pc,k} = -\delta q_{cc,k} \approx C_0 f(T) \left\{ 1 \text{ - } \exp\left(\frac{-q_{cc.k}{}^2}{q_{c,crit}^2 / f(T)^2} \right) \right\} q_{cc,k} \bullet \frac{\Delta z}{w_k}$$

Our model for the updraft velocity is much simpler than that employed by Sud and Walker. We simply integrate the buoyancy force in the vertical and scale the result by a tunable parameter.

Each plume modifies the environmental θ and q profiles. These modifications are felt by all subsequent plumes invoked during the call. In addition to the modification of the background thermodynamic state, the plumes detrain mass and condensate into the environment, so that net effects

$$DM = \sum_k D_k \,, \quad DC = \sum_k D_k q_{cc,k}$$

are obtained. DM and DC are passed to the large scale prognostic cloud scheme, PrognoCloud, to serve as sources for anvil cloud fraction and anvil cloud condensate. A net profile of precipitating convective condensate

$$P_{RAS} = \sum_k \delta q_{pc,k}$$

is also passed to PrognoCloud. Finally an estimate of updraft areal fractions is made using the total mass flux through each layer along with the local vertical velocity estimate.

Large-Scale Cloud Scheme

Source Terms for Cloud

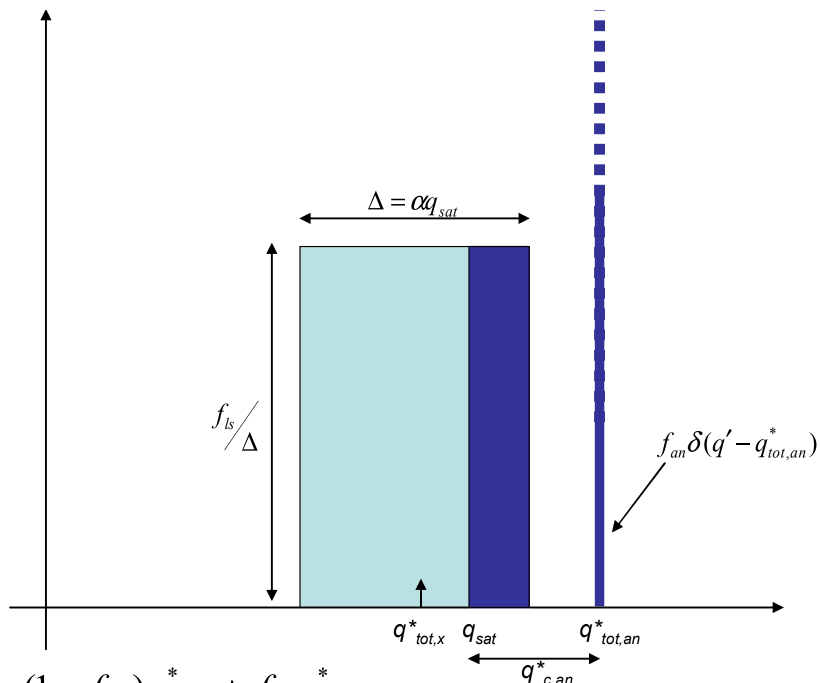
As described earlier the scheme distinguishes two types of cloud - that produced by detraining convection and that produced by large-scale condensation. The first type will be referred to as anvil cloud here and denoted by the subscript *an*. The second type - large-scale clouds, will be denoted by the subscript *ls*.

Anvil Cloud. Anvil cloud condensate $q_{c,an}$ and anvil cloud fraction f_{an} are updated straightforwardly using DM and DC from RAS

$$\delta f_{an} = {DM}\big/{\rho \Delta z} \,, \qquad \delta q_{c,an} = {DC}\big/{\rho \Delta z}$$

Large-Scale Condensation. Condensation is based on a PDF of total water as in Smith (1990) or Rotstayn (1999). However, Moist-1 uses a boxcar with a spread determined by the local saturation humidity, qsat. This aspect of the scheme has changed somewhat from NSIPP-2.

The current cloud scheme can be interpreted as a prognostic PDF scheme with a bi-modal structure as shown in the Figure below.



$$\overline{q}_{tot} = (1 - f_{an})q^*_{tot,x} + f_{an}q^*_{tot,an}$$

$$q^*_{tot,an} = q_{sat}(\overline{T}) + q^*_{c,an};\quad \overline{q}_{c,an} = f_{an}q^*_{c,an}$$

Schematic diagram of the implicit bi-modal PDF structure in the GEOS-5/Moist-1 cloud scheme. The current scheme consists of a boxcar PDF in non-anvil regions added to a δ-function containing contributions from detraining convection. In the symbols above, overbars refer to gridbox mean values.

Destruction of cloud

Destruction of cloud occurs in three ways: 1) evaporation "cloud munching"; 2) autoconversion of cloud condensate to precipitating condensate; 3) sedimentation of and 4) accretion of cloud condensate onto falling precipitation.

Evaporation of cloud (E_c) "munching" `(evap3)`.

This mechanism is meant to represent destruction of cloud along edges in contact with cloud-free air. We parameterize this process using a microphysical expression from Del Genio et al (1996)

$$E_c = -C_{E,c}\frac{1-U}{\rho_w(A+B)r_c^{\,2}}q_c$$

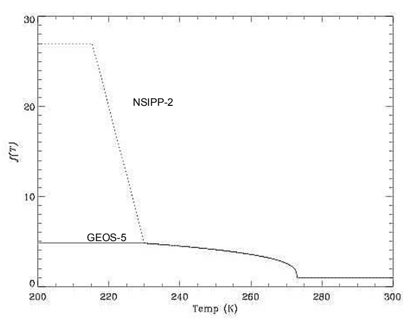
where U is an environmental relative humidity, $q_c$is the cloud condensate mixing ratio, r_c is the cloud droplet radius derived from an assumed number density, A and B are temperature dependent microphysical parameters. In GEOS5 this loss is applied only to the anvil type.

Autoconversion of liquid and mixed phase cloud (A_c) `(autocon3).`
This is parameterized using the same Sundqvist-type formulation as used in the convective parameterization.

$$A_c = C_{A0} f(T) \left\{ 1 \text{ - } \exp\left(\frac{-q_{c\{ls,an\}}^{\;2}}{q_{c,crit}^2 / f(T)^2} \right) \right\} q_{c\{ls,an\}}$$

The same temperature dependent factor *f(T)* is used for *ls* and *an* clouds. The behavior of *f* vs. *T* is shown is shown in the figure below. The increase below 273K represents accelerated production of precipitation in mixed-phase clouds. The choice of this function is largely empirical, and we intend to replace this formulation with more physically-based treatments in the near future. We do not consider destruction of cloud fraction by autoconversion.

In NSIPP-2 a third low-temperature regime was incorporated in the function *f(T)* (e.g. Sud and Walker 1999). This was meant to represent rapid conversion or fall out of frozen ice crystals. In GEOS-5 this process is handled explicitly using the sedimentation formulation described below.



"Sundquist-factor" controlling low-temperature autoconversion

Sedimentation of ice cloud (S_c). `(icefall, settle_vel).`
This is parameterized using cirrus ice fall speeds given by Lawrence and Crutzen (1998). However, instead of using their regime division based on latitude, we assign their expression for tropical cirrus to anvil clouds, and their mid-latitude form to large-scale clouds.

$$W_{F,c,i,an} = 128.6 + 53.2\log_{10}(q_{c,i,an}) + 5.5[\log_{10}(q_{c,i,an})]^2$$
$$W_{F,c,i,ls} = 106(q_{c,i,an})^{0.16}$$

We intended to use a simple one-way advection to represent the transition of ice cloud particles to sedimenting particles the - "fall through" approximation (e.g. Le Treut et al. 1994):

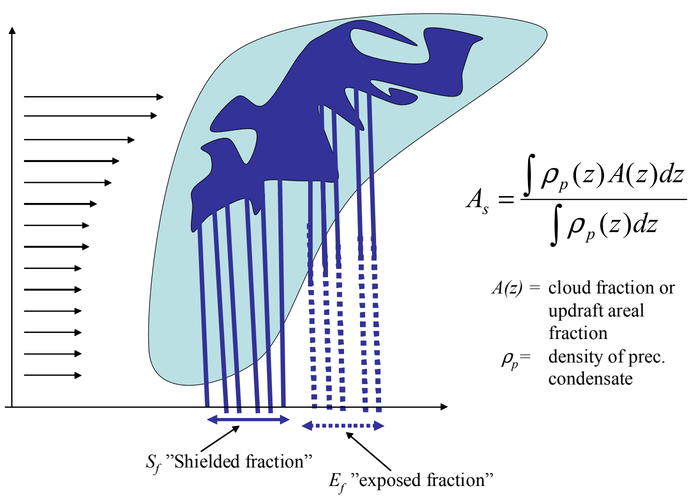
$$S_c = -C_S\, q_{c,i}\, \frac{V_F}{\Delta z}$$

with an empirically tuned parameter C_s. However, this leads to unacceptably rapid loss of frozen condensate for reasonable values of C_s (>1e-3). This approximation is known to overestimate production of frozen precipitation in other models (Rotstayn 1997). So, we are currently testing a slightly more complicated version including an estimated flux of ice from above.

Fall out and re-evaporation of precipitation and accretion of cloud condensate (`precip3`)

All precipitation, including that produced within convective plumes, is finally disposed of in PrognoCloud. Three streams of precipitation, each with two phases, are considered: liquid and frozen precipitating condensate from *ls* clouds - $q_{p,i,ls}$ $q_{p,l,ls}$; liquid and frozen precipitating condensate from *an* clouds - $q_{p,i,an}$ $q_{p,l,an}$, and liquid and frozen precipitating condensate from convective plumes (*cu*) - $q_{p,i,cu}$ $q_{p,l,cu}$.

The inputs to precip3 are mixing ratios of precipitating condensate. The precipitating condensate in each stream and phase is accumulated from the top assuming complete fallout to obtain the gridbox-mean, downward flux of precipitation at level *k*, $P^{\downarrow}_{box}(k)$. To account for subgrid scale variability in precipitation this flux is scaled by a "shower area factor", A_s defined below, $P^{\downarrow}_S = P^{\downarrow}_{box} A_S^{-1}$. This scaled flux is then used to estimate a typical drop size r_p using the Marshall-Palmer distribution. The quantity r_p is used to estimate precipitation fall velocities $W_{F,p}$ and ventilation factors Ve for the precipitation. These are now used along with the vertical width of layer k to estimate the fractional re-evaporation of precipitating condensate during its passage through the layer.



Schematic diagram of geometry assumed in rain re-evaporation calculation

$$\delta q_p = -C_{E,p} E_f Ve \frac{1-U}{\rho_w (A+B) r_p^{\,2}}\, q_p \left(\frac{\Delta z}{W_{F,p}} \right)$$

The shower area factor A_s is calculated slightly differently for convective and non-convective precipitation. For convective precipitation a weighted vertical mean of the updraft areal fraction is used. For non-convective precipitation, $q_{p,an}$ and $q_{p,ls}$, a similar weighted mean is calculated using the corresponding cloud fraction in place of updraft area fraction. The parameter E_f "exposed fraction" represents the fraction of precipitation exposed to grid box mean values of RH, as opposed to the shielded fraction $S_f = 1 - E_f$ which falls through a saturated cloudy environment. For nonconvective precipitation we assume $E_f = 1$. For convective precipitation a shear dependent exposure is assumed.

Accretion is parameterized simply using a Sundquist-style expression as in DelGenio et al (1996) or Sud and Walker (1999).

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